

Study on the influence of parameters of medical drill on bone drilling temperature

Xianchun XU^{1,2}, Yahui Hu^{1,2,3}, Jingwang Han^{1,2}, Lin Yue^{1,2}, and Wangbiao Jiang^{1,2}

1. Tianjin Key Laboratory of Design and Intelligent Control of Advanced Mechatronical System, Tianjin, 300384, China;
2. Tianjin University of Technology, 300384, China.

Email: huyahuilg@126.com

Abstract. During surgical interventions, the temperature generated during cortical bone drilling can affect the activity of bone material, which may lead to necrosis. In this paper, with the purpose of reducing the temperature during cortical bone drilling, the influence of the parameters of medical drill were analyzed. The finite element model of the drilling process was established based on the parametric design of the drill. The relationship between the drill bit diameter, the point angle, and the helix angle to the drilling temperature was studied by the center composite experiment. The results showed that the drilling temperature is increased with the increase of drill diameter, vertex angle and helix angle in the range of certain research.

1. Introduction

During surgical operations, drilling in the bone with medical twist drills is extensively carried out before some operations. Drilling force, temperature and quality are the important factors during the drilling process that could influence the integrity of the bone-impact interface[1].

Drilling temperature, which arises from shear deformations and the friction among the drill, bone debris and the bone, may lead to cell or bone necrosis[2-5] or cause ring sequestra around drilled hole[6]. There are studies in literatures about the registration of temperature during bone drilling that indicates thermal necrosis in cortical bone when this reached a temperature of 47°C for 60s[7-8]. Other authors showed that temperature above 55°C for a period longer than 30s can cause great irreversible lesions in bone tissue[7-9]. It is known that the heat generated in these processes is associated to the drilling parameters, such as rotational speed, feed rate, geometry of the drill bit, drill force, hole depth and the bone density[10].

The complex relationships among the geometry of the drill bit, drilling conditions, mechanism of the chip removal and the properties of the bone presents a great challenge in developing a mathematical model for the calculation of the heat generated during bone drilling[11]. Some studies showed that small angles drill has some advantages in drilling. The maximum axial force and temperature created by the drill with small angles is less than the ordinary standard twist drill, the damage area is smaller and the processing quality is better[12-13]. This paper intends to present an approach to developing a mathematical relationship between the temperature produced during cortical



bone drilling and the geometric parameters of medical drill such as diameter, point angle and helix angle by using response surface methodology.

2. FE model of drilling and experiments

2.1 Parametric design of the drill

The geometry and the parameters of the drill bit is shown in figure.1

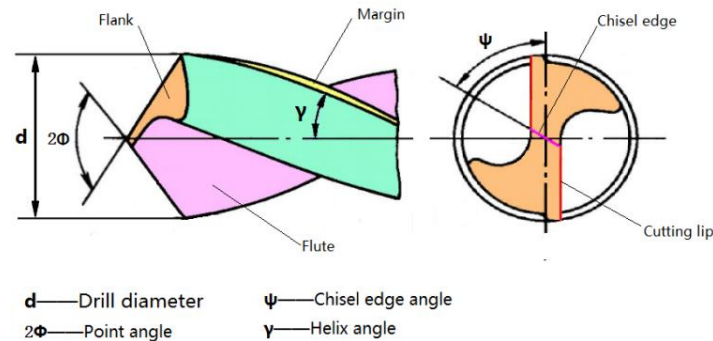


Figure 1. The geometry and the parameters of the drill bit

A 3D solid model with parametric design of the drill was established according to the mathematical model of its blade by UG\Open Grip. Some parameters to create the drill model we need were input from the human-computer interactive interface, shown as figure 2(a). Three drill models of different parameters created by this method, shown as figure 2(b).

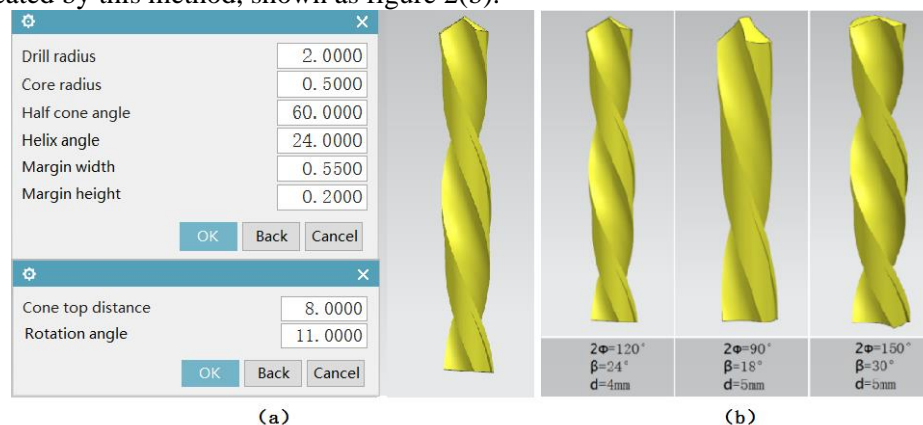


Figure 2. Models created by parametric design

Then the solid model of drill was saved as(.x_t) and transformed it into ABAQUS13.1. The model of cortical bone was replaced by the disk with a diameter of 10mm and a thickness of 4 mm[14].

2.2 Material properties

The material for the stainless steel medical twist drill is the 4Cr13. The cortical bone was modeled as transversely isotropic elasto-plastic rate dependent material to simplify our research[15]. The material properties of the two parts are shown in Table 1.

Table 1. Material properties

Material	Cortical bone	Drill
Density/ ($t \cdot mm^{-3}$)	2.00×10^{-9}	7.84×10^{-9}
Young's modulus/ MPa	20 000	210 000
Poisson's ratio	0.36	0.24
Plastic / MPa	106.99	585
Specific Heat / ($mJ \cdot t^{-1} \cdot ^\circ C^{-1}$)	1.26×10^9	4.90×10^8

Conductivity / ($\text{Watt} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$)	0.56	47.7
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2.3 Boundary condition and mesh

In the boundary conditions setting, the degrees of freedom on the sides of the cortical bone are fixed at all. The drill-bit was modeled as a rigid body (reference point is RP-1) because the elastic stiffness of the stainless steel twist drill-bit used is in the range of 200-220 GPa as compared to 20 GPa for the cortical bone; this reduces the computational cost involved in the highly resource consuming drilling simulations [16]. And the drill-bit was constrained to rotate only about its own longitudinal axis with a specified speed and feed vertically downwards into the work piece as shown in figure 3(a).

The material properties and the unit types were assigned to each parts. The drill-bit was modeled with Tet unit, the unit type is C3D4T and meshed with 23318 elements; The cutting area where the bone is in contact with the drill bit was modelled with Wedge unit, the unit type is C3D6T and meshed with 6688 elements; Other areas on the cortical bone was modeled with C3D8RT and meshed with 29440 elements. The meshing is shown in the figure 3(b). Contact between the drill and cortical bone was defined by the surface to surface contact algorithm available in Abaqus/explicit. And the frictional contact between the drill and cortical bone was modelled with a constant coefficient of friction of 0.7 [17].

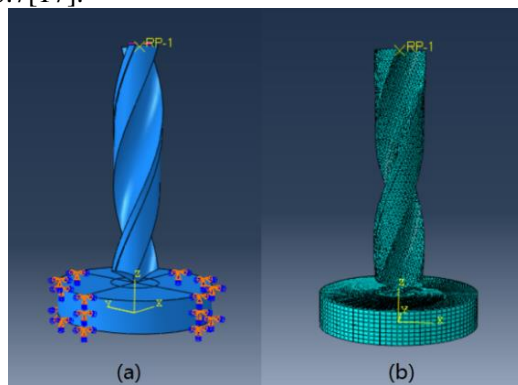


Figure 3. Boundary conditions and mesh

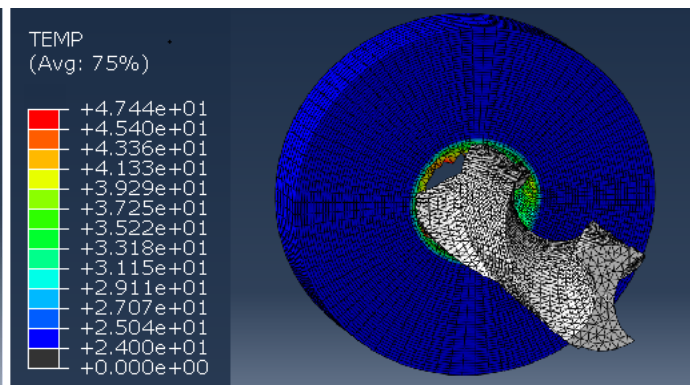


Figure 4. Cortical bone drilling temperature distribution

2.4 Experimental verification

In this simulation, the stainless steel 4Cr13 drill was used. And it had a diameter of 4mm, a point angle of 120° and a helix angle of 24° . Simulation was carried out at a speed of 1000rpm and a feed rate of 70mm/min. The initial temperature was set at 24°C . Running the model and the result was gotten as shown in figure 4. The maximum temperature of the drilling area after drilling is 47.44° .

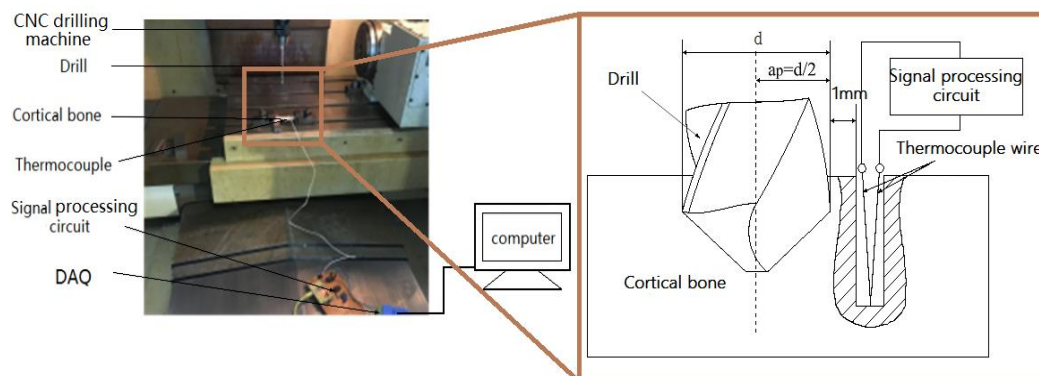
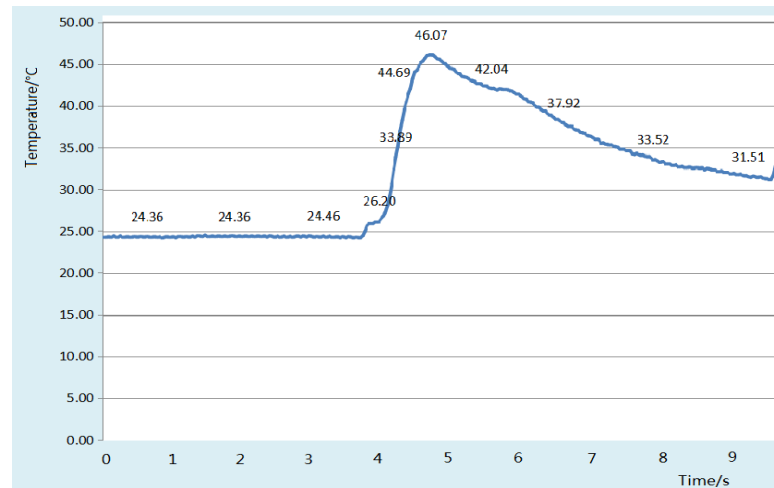


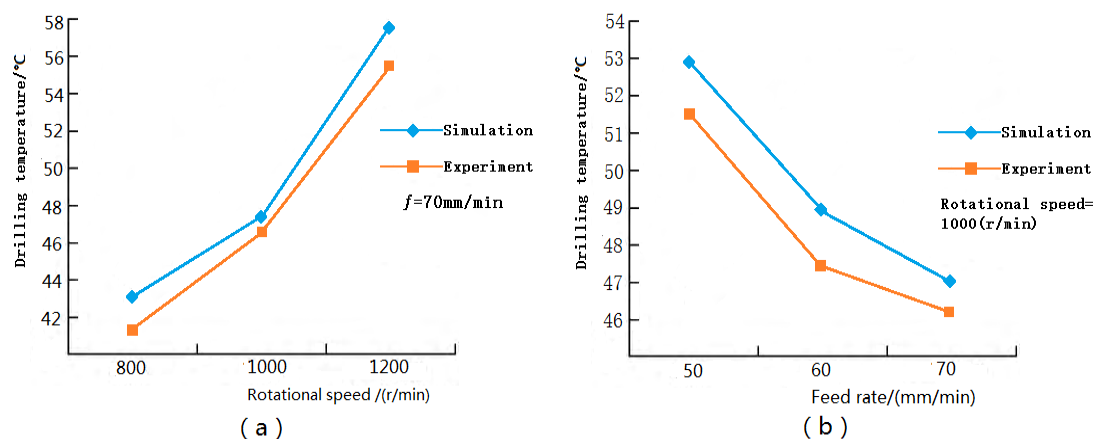
Figure 5. Measurement system of bone drilling temperature

The experiments were carried out on the YCM-V65A Vertical Machining Center, the parameters of the drill are the same as the simulation model. The measuring system consists of thermocouple sensor, signal processing circuit, DAQ card and a computer. The experimental setup is shown as figure 5.

**Figure 6.** Curve of drilling temperature

When the experiment was carried out at a speed of 1000rpm and a feed rate of 70mm/min, the maximum temperature of the cortical bone drilling zone measured by thermocouple method is 46.07°C. And figure 6. shows that the drilling temperature firstly increased rapidly to the maximum value and then decreased moderately.

Figure 7. is the comparisons between the experimental results and the FE simulation results. In the first set of the comparisons, we used the same feed rate(70mm/min) and drilling in the cortical bone specimens were carried out at drilling speed of 800rpm, 1000rpm, and 1200rpm. In the second set of the comparisons, we used the same speed(1000rpm) and the feed rates were taken as 50mm/min, 60mm/min, and 70mm/min. The similar results were gotten from FE modeling and experimental tests. So the simulation model based on ABAQUS is credible.

**Figure 7.** Comparisons of simulation results and experiment results

3. Results and Discussion

3.1 Experiment design and results

RSM is an aggregation of mathematical and statistical tools that are efficacious for the modeling and analysis of process in which a response is influenced by several variables and the objective is to optimize that response[18-19].In this research,the influence of drill diameter, point angle and helix angle on drilling temperature were studied. We set up the center composite experiment by the software Design-Expert.The drilling process dynamics model was established by using ABAQUS finite element software to get the prediction model of drilling temperature,which provides theoretical guidance for the optimization of medical drill bits. The experimental factor levels were given in Table 2.

Table 2. Factors and levels for drilling model

Experiment factor / level	-1.6818	-1	0	1	-1.6818
Diameter/d (mm)	2.32	3	4	5	5.68
Vertex/ 2Φ ($^{\circ}$)	69.55	90	120	150	170.45
Helix / β ($^{\circ}$)	13.91	18	24	30	34.09

According to the central composite experiment, the experimental scheme of Table 3. was obtained. The drilling were carried out at rotational speed of 1000rpm and feed rate of 70mm/min. All simulations were performed at room temperature(24 $^{\circ}$ C). The ABAQUS was used to calculated the schemes one by one, and the results were shown in the Table 3.

Table 3. Experimental conditions and results

Std	Run	Diameter d (mm)	Point angle 2Φ ($^{\circ}$)	Helix angle β ($^{\circ}$)	Temperature ($^{\circ}$ C)
6	1	5.00	150.00	18.00	46.00
4	2	3.00	150.00	30.00	42.31
15	3	4.00	120.00	24.00	47.44
8	4	5.00	150.00	30.00	50.78
19	5	4.00	120.00	24.00	47.44
12	6	4.00	120.00	34.09	42.56
13	7	2.32	120.00	24.00	36.30
20	8	4.00	120.00	24.00	47.44
2	9	3.00	150.00	18.00	42.57
5	10	5.00	90.00	18.00	42.00
11	11	4.00	120.00	13.91	43.03
10	12	4.00	170.45	24.00	49.53
3	13	3.00	90.00	30.00	37.74
18	14	4.00	120.00	24.00	47.44
14	15	5.68	120.00	24.00	45.93
17	16	4.00	120.00	24.00	47.44
7	17	5.00	90.00	30.00	46.48
1	18	3.00	90.00	18.00	35.69
9	19	4.00	69.55	24.00	39.22
16	20	4.00	120.00	24.00	47.44

3.2 Response surface analysis

The results of Table 3 were input to the experimental design software(Design-Expert 8.0.6)for analysis.The quadratic regression equation of drilling temperature is shown as(1).

$$T = -26.49 + 0.42\Phi + 1.65\beta + 17.63d - 1.39 \times 10^{-3}\Psi \cdot \beta - 1.31 \times 10^{-2}\Psi \cdot d + 0.15\beta \cdot d - 1.03 \times 10^{-3}\Psi^2 - 4.12 \times 10^{-2}\beta^2 - 2.08d^2 \quad (1)$$

Where: Ψ (2Φ) — Point angle (°).

The ANOVA results for the response surface model were given in Table 4. F is the significance, P is the confidence level. And the P value of the model is <0.0001 which means that the factor is significant. In this case A,C,A²,B² and C² are significant model factors.

Table 4. AVOVA table for quadratic model

Source	Sum of Squares	df	Mean Square	F-value	P-value (Prob>F)	
Model	344.96	9	38.33	34.18	<0.0001	significant
A-Point angle	100.73	1	100.73	89.82	<0.0001	
B-Helix angle	7.71	1	7.71	6.87	0.0255	
C-Diameter	136.31	1	136.31	121.55	<0.0001	
AB	0.51	1	0.51	0.45	0.5174	
AC	1.24	1	1.24	1.11	0.3177	
BC	6.98	1	6.98	6.22	0.0318	
A ²	12.38	1	12.38	11.04	0.0077	
B ²	31.80	1	31.80	28.36	0.0003	
C ²	62.32	1	62.32	55.57	<0.0001	

The plot of the residuals against the predicted temperature is shown in figure 8. The figure shows that the residual points distributed near a straight line. So the model proposed predicts of the temperature with reasonable accuracy and can be effectively used for the prediction of temperature during bone drilling. The above mathematical model can be used to predict the values of the drilling temperature within the limits of the factors studied.

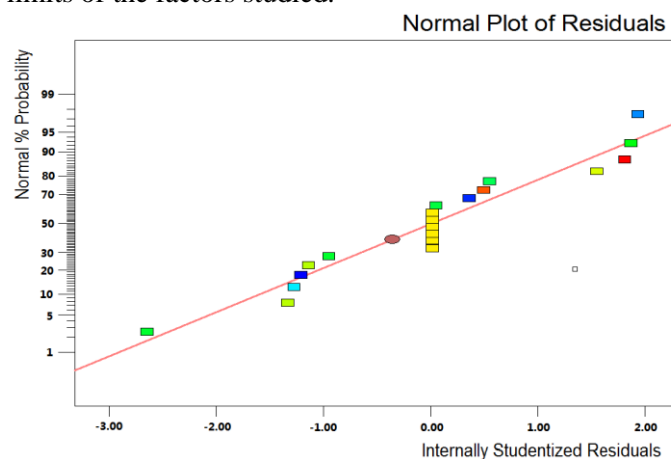


Figure 8. Curve of drilling temperature

The response surface plots obtained by the modeling of temperature in cortical bone drilling are shown in figure 9. It can be seen from the figure that the drilling temperature increases with the increase of the drill diameter, the point angle and the helix angle within the limits of the factors studied. The drill-bit diameter and the point angle have a great influence on the drilling temperature, and the helix angle has little effect on the drilling temperature.

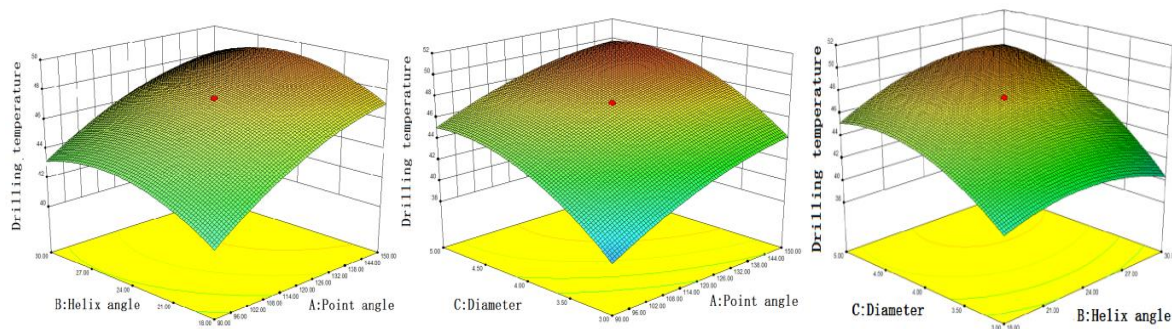


Figure 9. Response surface plots of drilling temperature during bone drilling as a function of point angle, helix angle and diameter.

4. Conclusions

In this paper, with the aim of decreasing the temperature during cortical bone drilling, a surgical drill bit has been optimized, the influence of the drill diameter, the point angle and the helix angle on the drilling temperature were analyzed. The following observations can be made in this research:

- The finite element model of drilling on cortical bone was developed using a FE software Abaqus/Explicit based on the three-dimensional solid model of the drill with parametric design. The parameters that can be controlled are diameter, point angle and helix angle.
- The finite element model predicted cortical bone drilling temperature with reasonable accuracy when compared to the experimental results.
- The contribution of each factor and their interaction on the temperature produced during cortical bone drilling was evaluated by using RSM. It was observed that the drilling temperature increased with an increased in diameter, point angle and helix angle. The drill diameter has the highest influence on drilling temperature, followed by the point angle and the helix angle has a insignificant influence on drilling temperature.

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